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Understanding the LINUX KERNEL

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DANIEL P. BOVET & MARCO CESATI

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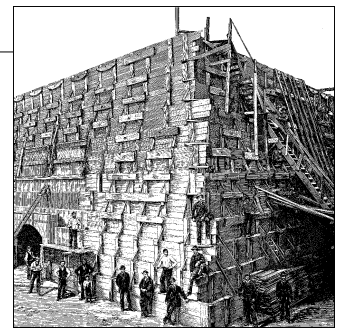
CHAPTER 17

The Ext2 and Ext3 Filesystems



In this chapter, we finish our extensive discussion of I/O and filesystems by taking a look at the details the kernel has to take care of when interacting with a particular filesystem. Since the Second Extended Filesystem (Ext2) is native to Linux and is used on virtually every Linux system, it is a natural choice for this discussion. Furthermore, Ext2 illustrates a lot of good practices in its support for modern filesystem features with fast performance. To be sure, other filesystems will embody new and interesting requirements because they are designed for other operating systems, but we cannot examine the oddities of various filesystems and platforms in this book.

After introducing Ext2 in the section "General Characteristics of Ext2," we describe the data structures needed, just as in other chapters. Since we are looking at a particular way to store data on a disk, we have to consider two versions of data structures. The section "Ext2 Disk Data Structures" shows the data structures stored by Ext2 on the disk, while "Ext2 Memory Data Structures" shows how they are duplicated in memory.

Then we get to the operations performed on the filesystem. In the section "Creating the Ext2 Filesystem," we discuss how Ext2 is created in a disk partition. The next sections describe the kernel activities performed whenever the disk is used. Most of these are relatively low-level activities dealing with the allocation of disk space to inodes and data blocks.

In the last section, we give a short description of the Ext3 filesystem, which is the next step in the evolution of the Ext2 filesystem.

General Characteristics of Ext2

Unix-like operating systems use several filesystems. Although the files of all such filesystems have a common subset of attributes required by a few POSIX APIs like `stat( )`, each filesystem is implemented in a different way.

The first versions of Linux were based on the Minix filesystem. As Linux matured, the *Extended Filesystem (Ext FS)* was introduced; it included several significant

extensions, but offered unsatisfactory performance. The *Second Extended Filesystem (Ext2)* was introduced in 1994; besides including several new features, it is quite efficient and robust and has become the most widely used Linux filesystem.

The following features contribute to the efficiency of Ext2:

- When creating an Ext2 filesystem, the system administrator may choose the optimal block size (from 1,024 to 4,096 bytes), depending on the expected average file length. For instance, a 1,024-block size is preferable when the average file length is smaller than a few thousand bytes because this leads to less internal fragmentation—that is, less of a mismatch between the file length and the portion of the disk that stores it (see the section "Memory Area Management" in Chapter 7, where internal fragmentation for dynamic memory was discussed). On the other hand, larger block sizes are usually preferable for files greater than a few thousand bytes because this leads to fewer disk transfers, thus reducing system overhead.
- When creating an Ext2 filesystem, the system administrator may choose how many inodes to allow for a partition of a given size, depending on the expected number of files to be stored on it. This maximizes the effectively usable disk space.
- The filesystem partitions disk blocks into groups. Each group includes data blocks and inodes stored in adjacent tracks. Thanks to this structure, files stored in a single block group can be accessed with a lower average disk seek time.
- The filesystem *preallocates* disk data blocks to regular files before they are actually used. Thus, when the file increases in size, several blocks are already reserved at physically adjacent positions, reducing file fragmentation.
- Fast symbolic links are supported. If the pathname of the symbolic link (see the section "Hard and Soft Links" in Chapter 1) has 60 bytes or less, it is stored in the inode and can thus be translated without reading a data block.

Moreover, the Second Extended File System includes other features that make it both robust and flexible:

- A careful implementation of the file-updating strategy that minimizes the impact of system crashes. For instance, when creating a new hard link for a file, the counter of hard links in the disk inode is incremented first, and the new name is added into the proper directory next. In this way, if a hardware failure occurs after the inode update but before the directory can be changed, the directory is consistent, even if the inode's hard link counter is wrong. Deleting the file does not lead to catastrophic results, although the file's data blocks cannot be automatically reclaimed. If the reverse were done (changing the directory before updating the inode), the same hardware failure would produce a dangerous inconsistency: deleting the original hard link would remove its data blocks from disk, yet the new directory entry would refer to an inode that no longer exists. If that inode number were used later for another file, writing into the stale directory entry would corrupt the new file.

- Support for automatic consistency checks on the filesystem status at boot time. The checks are performed by the *e2fsck* external program, which may be activated not only after a system crash, but also after a predefined number of filesystem mountings (a counter is incremented after each mount operation) or after a predefined amount of time has elapsed since the most recent check.
- Support for immutable files (they cannot be modified, deleted, or renamed) and for append-only files (data can be added only to the end of them).
- Compatibility with both the Unix System V Release 4 and the BSD semantics of the Group ID for a new file. In SVR4, the new file assumes the Group ID of the process that creates it; in BSD, the new file inherits the Group ID of the directory containing it. Ext2 includes a mount option that specifies which semantic is used.

The Ext2 filesystem is a mature, stable program, and it has not evolved significantly in recent years. Several additional features, however, have been considered for inclusion. Some of them have already been coded and are available as external patches. Others are just planned, but in some cases, fields have already been introduced in the Ext2 inode for them. The most significant features being considered are:

Block fragmentation
: System administrators usually choose large block sizes for accessing disks because computer applications often deal with large files. As a result, small files stored in large blocks waste a lot of disk space. This problem can be solved by allowing several files to be stored in different fragments of the same block.

Access Control Lists (ACL)
: Instead of classifying the users of a file under three classes—owner, group, and others—this list is associated with each file to specify the access rights for any specific users or combinations of users.

Handling of transparently compressed and encrypted files
: These new options, which must be specified when creating a file, allow users to transparently store compressed and/or encrypted versions of their files on disk.

Logical deletion
: An *undelete* option allows users to easily recover, if needed, the contents of a previously removed file.

Journaling
: Journaling avoids the time-consuming check that is automatically performed on a filesystem when it is abruptly unmounted—for instance, as a consequence of a system crash.

In practice, none of these features has been officially included in the Ext2 filesystem. One might say that Ext2 is victim of its success; it is still the preferred filesystem adopted by most Linux distribution companies, and the millions of users who use it every day would look suspiciously at any attempt to replace Ext2 with some other filesystem that has not been so heavily tested and used.

A self-evident example of this phenomenon is journaling, which is the most compelling feature required by high-availability servers. Journaling has not been introduced in the Ext2 filesystem; rather, as we shall discuss in the later section "The Ext3 Filesystem," a new filesystem that is fully compatible with Ext2 has been created, which also offers journaling. Users who do not really require journaling may continue to use the good old Ext2 filesystem, while the others will likely adopt the new filesystem.

Ext2 Disk Data Structures

The first block in any Ext2 partition is never managed by the Ext2 filesystem, since it is reserved for the partition boot sector (see Appendix A). The rest of the Ext2 partition is split into *block groups*, each of which has the layout shown in Figure 17-1. As you will notice from the figure, some data structures must fit in exactly one block, while others may require more than one block. All the block groups in the filesystem have the same size and are stored sequentially, thus the kernel can derive the location of a block group in a disk simply from its integer index.

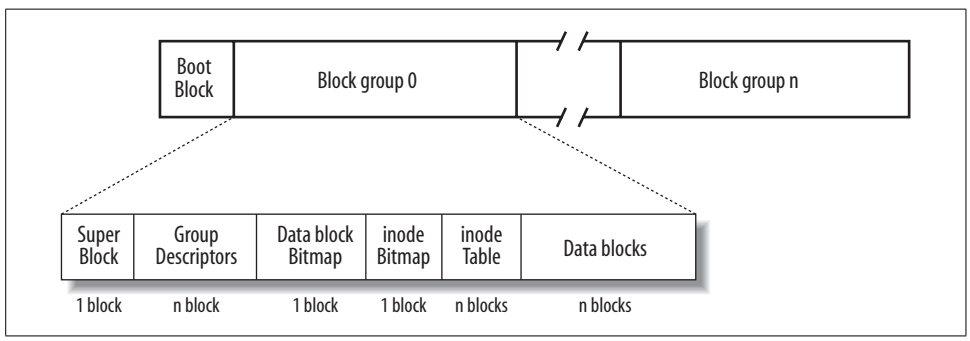


Figure 17-1. Layouts of an Ext2 partition and of an Ext2 block group

Block groups reduce file fragmentation, since the kernel tries to keep the data blocks belonging to a file in the same block group, if possible. Each block in a block group contains one of the following pieces of information:

- A copy of the filesystem's superblock
- A copy of the group of block group descriptors
- A data block bitmap
- A group of inodes
- An inode bitmap
- A chunk of data that belongs to a file; i.e., a data block

If a block does not contain any meaningful information, it is said to be free.

As can be seen from Figure 17-1, both the superblock and the group descriptors are duplicated in each block group. Only the superblock and the group descriptors

included in block group 0 are used by the kernel, while the remaining superblocks and group descriptors are left unchanged; in fact, the kernel doesn't even look at them. When the *e2fsck* program executes a consistency check on the filesystem status, it refers to the superblock and the group descriptors stored in block group 0, and then copies them into all other block groups. If data corruption occurs and the main superblock or the main group descriptors in block group 0 becomes invalid, the system administrator can instruct *e2fsck* to refer to the old copies of the superblock and the group descriptors stored in a block groups other than the first. Usually, the redundant copies store enough information to allow *e2fsck* to bring the Ext2 partition back to a consistent state.

How many block groups are there? Well, that depends both on the partition size and the block size. The main constraint is that the block bitmap, which is used to identify the blocks that are used and free inside a group, must be stored in a single block. Therefore, in each block group, there can be at most $8 \times b$ blocks, where b is the block size in bytes. Thus, the total number of block groups is roughly $s/(8 \times b)$, where s is the partition size in blocks.

For example, let's consider an 8 GB Ext2 partition with a 4-KB block size. In this case, each 4-KB block bitmap describes 32K data blocks—that is, 128 MB. Therefore, at most 64 block groups are needed. Clearly, the smaller the block size, the larger the number of block groups.

Superblock

An Ext2 disk superblock is stored in an `ext2_super_block` structure, whose fields are listed in Table 17-1. The `__u8`, `__u16`, and `__u32` data types denote unsigned numbers of length 8, 16, and 32 bits respectively, while the `__s8`, `__s16`, `__s32` data types denote signed numbers of length 8, 16, and 32 bits.

Table 17-1. The fields of the Ext2 superblock

Type	Field	Description
`__u32`	`s_inodes_count`	Total number of inodes
`__u32`	`s_blocks_count`	Filesystem size in blocks
`__u32`	`s_r_blocks_count`	Number of reserved blocks
`__u32`	`s_free_blocks_count`	Free blocks counter
`__u32`	`s_free_inodes_count`	Free inodes counter
`__u32`	`s_first_data_block`	Number of first useful block (always 1)
`__u32`	`s_log_block_size`	Block size
`__s32`	`s_log_frag_size`	Fragment size
`__u32`	`s_blocks_per_group`	Number of blocks per group
`__u32`	`s_frags_per_group`	Number of fragments per group
`__u32`	`s_inodes_per_group`	Number of inodes per group

Table 17-1. The fields of the Ext2 superblock (continued)

Type	Field	Description
__u32	s_mtime	Time of last mount operation
__u32	s_wtime	Time of last write operation
__u16	s_mnt_count	Mount operations counter
__u16	s_max_mnt_count	Number of mount operations before check
__u16	s_magic	Magic signature
__u16	s_state	Status flag
__u16	s_errors	Behavior when detecting errors
__u16	s_minor_rev_level	Minor revision level
__u32	s_lastcheck	Time of last check
__u32	s_checkinterval	Time between checks
__u32	s_creator_os	OS where filesystem was created
__u32	s_rev_level	Revision level
__u16	s_def_resuid	Default UID for reserved blocks
__u16	s_def_resgid	Default GID for reserved blocks
__u32	s_first_ino	Number of first nonreserved inode
__u16	s_inode_size	Size of on-disk inode structure
__u16	s_block_group_nr	Block group number of this superblock
__u32	s_feature_compat	Compatible features bitmap
__u32	s_feature_incompat	Incompatible features bitmap
__u32	s_feature_ro_compat	Read-only compatible features bitmap
__u8 [16]	s_uuid	128-bit filesystem identifier
char [16]	s_volume_name	Volume name
char [64]	s_last_mounted	Pathname of last mount point
__u32	s_algorithm_usage_bitmap	Used for compression
__u8	s_prealloc_blocks	Number of blocks to preallocate
__u8	s_prealloc_dir_blocks	Number of blocks to preallocate for directories
__u16	s_padding1	Alignment to word
__u32 [204]	s_reserved	Nulls to pad out 1,024 bytes

The `s_inodes_count` field stores the number of inodes, while the `s_blocks_count` field stores the number of blocks in the Ext2 filesystem.

The `s_log_block_size` field expresses the block size as a power of 2, using 1,024 bytes as the unit. Thus, 0 denotes 1,024-byte blocks, 1 denotes 2,048-byte blocks, and so on. The `s_log_frag_size` field is currently equal to `s_log_block_size`, since block fragmentation is not yet implemented.

The `s_blocks_per_group`, `s_frags_per_group`, and `s_inodes_per_group` fields store the number of blocks, fragments, and inodes in each block group, respectively.

Some disk blocks are reserved to the superuser (or to some other user or group of users selected by the s_def_resuid and s_def_resgid fields). These blocks allow the system administrator to continue to use the filesystem even when no more free blocks are available for normal users.

The s_mnt_count, s_max_mnt_count, s_lastcheck, and s_checkinterval fields set up the Ext2 filesystem to be checked automatically at boot time. These fields cause *e2fsck* to run after a predefined number of mount operations has been performed, or when a predefined amount of time has elapsed since the last consistency check. (Both kinds of checks can be used together.) The consistency check is also enforced at boot time if the filesystem has not been cleanly unmounted (for instance, after a system crash) or when the kernel discovers some errors in it. The s_state field stores the value 0 if the filesystem is mounted or was not cleanly unmounted, 1 if it was cleanly unmounted, and 2 if it contains errors.

Group Descriptor and Bitmap

Each block group has its own group descriptor, an ext2_group_desc structure whose fields are illustrated in Table 17-2.

Table 17-2. The fields of the Ext2 group descriptor

Type	Field	Description
__u32	bg_block_bitmap	Block number of block bitmap
__u32	bg_inode_bitmap	Block number of inode bitmap
__u32	bg_inode_table	Block number of first inode table block
__u16	bg_free_blocks_count	Number of free blocks in the group
__u16	bg_free_inodes_count	Number of free inodes in the group
__u16	bg_used_dirs_count	Number of directories in the group
__u16	bg_pad	Alignment to word
__u32 [3]	bg_reserved	Nulls to pad out 24 bytes

The bg_free_blocks_count, bg_free_inodes_count, and bg_used_dirs_count fields are used when allocating new inodes and data blocks. These fields determine the most suitable block in which to allocate each data structure. The bitmaps are sequences of bits, where the value 0 specifies that the corresponding inode or data block is free and the value 1 specifies that it is used. Since each bitmap must be stored inside a single block and since the block size can be 1,024, 2,048, or 4,096 bytes, a single bitmap describes the state of 8,192, 16,384, or 32,768 blocks.

Inode Table

The inode table consists of a series of consecutive blocks, each of which contains a predefined number of inodes. The block number of the first block of the inode table is stored in the bg_inode_table field of the group descriptor.

All inodes have the same size: 128 bytes. A 1,024-byte block contains 8 inodes, while a 4,096-byte block contains 32 inodes. To figure out how many blocks are occupied by the inode table, divide the total number of inodes in a group (stored in the `s_inodes_per_group` field of the superblock) by the number of inodes per block.

Each Ext2 inode is an `ext2_inode` structure whose fields are illustrated in Table 17-3.

Table 17-3. The fields of an Ext2 disk inode

Type	Field	Description
`__u16`	`i_mode`	File type and access rights
`__u16`	`i_uid`	Owner identifier
`__u32`	`i_size`	File length in bytes
`__u32`	`i_atime`	Time of last file access
`__u32`	`i_ctime`	Time that inode last changed
`__u32`	`i_mtime`	Time that file contents last changed
`__u32`	`i_dtime`	Time of file deletion
`__u16`	`i_gid`	Group identifier
`__u16`	`i_links_count`	Hard links counter
`__u32`	`i_blocks`	Number of data blocks of the file
`__u32`	`i_flags`	File flags
`union`	`osd1`	Specific operating system information
`__u32 [EXT2_N_BLOCKS]`	`i_block`	Pointers to data blocks
`__u32`	`i_generation`	File version (used when the file is accessed by a network filesystem)
`__u32`	`i_file_acl`	File access control list
`__u32`	`i_dir_acl`	Directory access control list
`__u32`	`i_faddr`	Fragment address
`union`	`osd2`	Specific operating system information

Many fields related to POSIX specifications are similar to the corresponding fields of the VFS's inode object and have already been discussed in the section "Inode Objects" in Chapter 12. The remaining ones refer to the Ext2-specific implementation and deal mostly with block allocation.

In particular, the `i_size` field stores the effective length of the file in bytes, while the `i_blocks` field stores the number of data blocks (in units of 512 bytes) that have been allocated to the file.

The values of `i_size` and `i_blocks` are not necessarily related. Since a file is always stored in an integer number of blocks, a nonempty file receives at least one data block (since fragmentation is not yet implemented) and `i_size` may be smaller than 512×`i_blocks`. On the other hand, as we shall see in the section "File Holes" later in this chapter, a file may contain holes. In that case, `i_size` may be greater than 512×`i_blocks`.

The i_block field is an array of EXT2_N_BLOCKS (usually 15) pointers to blocks used to identify the data blocks allocated to the file (see the section "Data Blocks Addressing" later in this chapter).

The 32 bits reserved for the i_size field limit the file size to 4 GB. Actually, the highest-order bit of the i_size field is not used, so the maximum file size is limited to 2 GB. However, the Ext2 filesystem includes a "dirty trick" that allows larger files on 64-bit architectures like Hewlett-Packard's Alpha. Essentially, the i_dir_acl field of the inode, which is not used for regular files, represents a 32-bit extension of the i_size field. Therefore, the file size is stored in the inode as a 64-bit integer. The 64-bit version of the Ext2 filesystem is somewhat compatible with the 32-bit version because an Ext2 filesystem created on a 64-bit architecture may be mounted on a 32-bit architecture, and vice versa. On a 32-bit architecture, a large file cannot be accessed, unless opening the file with the O_LARGEFILE flag set (see the section "The open() System Call" in Chapter 12).

Recall that the VFS model requires each file to have a different inode number. In Ext2, there is no need to store on disk a mapping between an inode number and the corresponding block number because the latter value can be derived from the block group number and the relative position inside the inode table. For example, suppose that each block group contains 4,096 inodes and that we want to know the address on disk of inode 13,021. In this case, the inode belongs to the third block group and its disk address is stored in the 733rd entry of the corresponding inode table. As you can see, the inode number is just a key used by the Ext2 routines to retrieve the proper inode descriptor on disk quickly.

How Various File Types Use Disk Blocks

The different types of files recognized by Ext2 (regular files, pipes, etc.) use data blocks in different ways. Some files store no data and therefore need no data blocks at all. This section discusses the storage requirements for each type, which are listed in Table 17-4.

Table 17-4. Ext2 file types

File_type	Description
0	Unknown
1	Regular file
2	Directory
3	Character device
4	Block device
5	Named pipe
6	Socket
7	Symbolic link

Regular file

Regular files are the most common case and receive almost all the attention in this chapter. But a regular file needs data blocks only when it starts to have data. When first created, a regular file is empty and needs no data blocks; it can also be emptied by the `truncate()` or `open()` system calls. Both situations are common; for instance, when you issue a shell command that includes the string >*filename*, the shell creates an empty file or truncates an existing one.

Directory

Ext2 implements directories as a special kind of file whose data blocks store filenames together with the corresponding inode numbers. In particular, such data blocks contain structures of type `ext2_dir_entry_2`. The fields of that structure are shown in Table 17-5. The structure has a variable length, since the last `name` field is a variable length array of up to `EXT2_NAME_LEN` characters (usually 255). Moreover, for reasons of efficiency, the length of a directory entry is always a multiple of 4 and, therefore, null characters (`\0`) are added for padding at the end of the filename, if necessary. The `name_len` field stores the actual file name length (see Figure 17-2).

Table 17-5. The fields of an Ext2 directory entry

Type	Field	Description
`__u32`	`inode`	Inode number
`__u16`	`rec_len`	Directory entry length
`__u8`	`name_len`	Filename length
`__u8`	`file_type`	File type
`char [EXT2_NAME_LEN]`	`name`	Filename

The `file_type` field stores a value that specifies the file type (see Table 17-4). The `rec_len` field may be interpreted as a pointer to the next valid directory entry: it is the offset to be added to the starting address of the directory entry to get the starting address of the next valid directory entry. To delete a directory entry, it is sufficient to set its `inode` field to 0 and suitably increment the value of the `rec_len` field of the previous valid entry. Read the `rec_len` field of Figure 17-2 carefully; you'll see that the *oldfile* entry was deleted because the `rec_len` field of *usr* is set to 12+16 (the lengths of the *usr* and *oldfile* entries).

Symbolic link

As stated before, if the pathname of the symbolic link has up to 60 characters, it is stored in the `i_block` field of the inode, which consists of an array of 15 4-byte integers; no data block is therefore required. If the pathname is longer than 60 characters, however, a single data block is required.

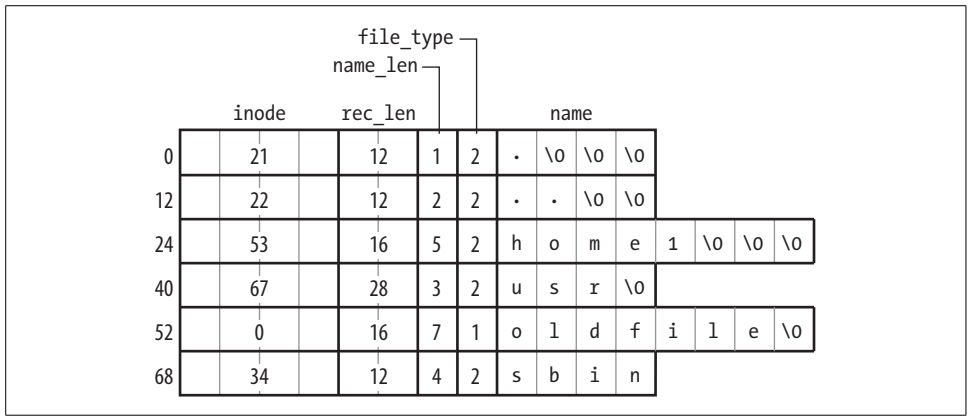


Figure 17-2. An example of the EXT2 directory

Device file, pipe, and socket

No data blocks are required for these kinds of files. All the necessary information is stored in the inode.

Ext2 Memory Data Structures

For the sake of efficiency, most information stored in the disk data structures of an Ext2 partition are copied into RAM when the filesystem is mounted, thus allowing the kernel to avoid many subsequent disk read operations. To get an idea of how often some data structures change, consider some fundamental operations:

- When a new file is created, the values of the `s_free_inodes_count` field in the Ext2 superblock and of the `bg_free_inodes_count` field in the proper group descriptor must be decremented.
- If the kernel appends some data to an existing file so that the number of data blocks allocated for it increases, the values of the `s_free_blocks_count` field in the Ext2 superblock and of the `bg_free_blocks_count` field in the group descriptor must be modified.
- Even just rewriting a portion of an existing file involves an update of the `s_wtime` field of the Ext2 superblock.

Since all Ext2 disk data structures are stored in blocks of the Ext2 partition, the kernel uses the buffer cache and the page cache to keep them up to date (see the section "Writing Dirty Buffers to Disk" in Chapter 14).

Table 17-6 specifies, for each type of data related to Ext2 filesystems and files, the data structure used on the disk to represent its data, the data structure used by the kernel in memory, and a rule of thumb used to determine how much caching is used. Data that is updated very frequently is always cached; that is, the data is permanently

stored in memory and included in the buffer cache or in the page cache until the corresponding Ext2 partition is unmounted. The kernel gets this result by keeping the buffer's usage counter greater than 0 at all times.

Table 17-6. VFS images of Ext2 data structures

Type	Disk data structure	Memory data structure	Caching mode
Superblock	`ext2_super_block`	`ext2_sb_info`	Always cached
Group descriptor	`ext2_group_desc`	`ext2_group_desc`	Always cached
Block bitmap	Bit array in block	Bit array in buffer	Fixed limit
Inode bitmap	Bit array in block	Bit array in buffer	Fixed limit
Inode	`ext2_inode`	`ext2_inode_info`	Dynamic
Data block	Unspecified	Buffer page	Dynamic
Free inode	`ext2_inode`	None	Never
Free block	Unspecified	None	Never

The never-cached data is not kept in any cache since it does not represent meaningful information.

In between these extremes lie two other modes: *fixed-limit* and *dynamic*. In the fixed-limit mode, a specific number of data structures can be kept in the buffer cache; older ones are flushed to disk when the number is exceeded. In the dynamic mode, the data is kept in a cache as long as the associated object (an inode or data block) is in use; when the file is closed or the data block is deleted, the `shrink_mmap()` function may remove the associated data from the cache and write it back to disk.

The ext2_sb_info and ext2_inode_info Structures

When an Ext2 filesystem is mounted, the `u` field of the VFS superblock, which contains filesystem-specific data, is loaded with a structure of type `ext2_sb_info` so that the kernel can find out things related to the filesystem as a whole. This structure includes the following information:

- Most of the disk superblock fields
- The block bitmap cache, tracked by the `s_block_bitmap` and `s_block_bitmap_number` arrays (see the next section)
- The inode bitmap cache, tracked by the `s_inode_bitmap` and `s_inode_bitmap_number` arrays (see the next section)
- An `s_sbh` pointer to the buffer head of the buffer containing the disk superblock
- An `s_es` pointer to the buffer containing the disk superblock
- The number of group descriptors, `s_desc_per_block`, that can be packed in a block

- An `s_group_desc` pointer to an array of buffer heads of buffers containing the group descriptors (usually, a single entry is sufficient)
- Other data related to mount state, mount options, and so on

Similarly, when an inode object pertaining to an Ext2 file is initialized, the `u` field is loaded with a structure of type `ext2_inode_info`, which includes this information:

- Most of the fields found in the disk's inode structure that are not kept in the generic VFS inode object (see Table 12-3 in Chapter 12)
- The fragment size and the fragment number (not yet used)
- The `block_group` block group index at which the inode belongs (see the section "Ext2 Disk Data Structures" earlier in this chapter)
- The `i_prealloc_block` and `i_prealloc_count` fields, which are used for data block preallocation (see the section "Allocating a Data Block" later in this chapter)
- The `i_osync` field, which is a flag specifying whether the disk inode should be synchronously updated

Bitmap Caches

When the kernel mounts an Ext2 filesystem, it allocates a buffer for the Ext2 disk superblock and reads its contents from disk. The buffer is released only when the Ext2 filesystem is unmounted. When the kernel must modify a field in the Ext2 superblock, it simply writes the new value in the proper position of the corresponding buffer and then marks the buffer as dirty.

Unfortunately, this approach cannot be adopted for all Ext2 disk data structures. The tenfold increase in disk capacity reached in recent years has induced a tenfold increase in the size of inode and data block bitmaps, so we have reached the point at which it is no longer convenient to keep all the bitmaps in RAM at the same time.

For instance, consider a 4-GB disk with a 1-KB block size. Since each bitmap fills all the bits of a single block, each of them describes the status of 8,192 blocks—that is, of 8 MB of disk storage. The number of block groups is 4,096 MB/8 MB=512. Since each block group requires both an inode bitmap and a data block bitmap, 1 MB of RAM would be required to store all 1,024 bitmaps in memory.

The solution adopted to limit the memory requirements of the Ext2 descriptors is to use, for any mounted Ext2 filesystem, two caches of size `EXT2_MAX_GROUP_LOADED` (usually 8). One cache stores the most recently accessed inode bitmaps, while the other cache stores the most recently accessed block bitmaps. Buffers that contain bitmaps included in a cache have a usage counter greater than 0, therefore they are never freed by `shrink_mmap()` (see the section "Reclaiming Page Frame" in Chapter 16). Conversely, buffers that contain bitmaps not included in a bitmap cache have a null usage counter, so they can be freed if free memory becomes scarce.

Each cache is implemented by means of two arrays of EXT2_MAX_GROUP_LOADED elements. One array contains the indexes of the block groups whose bitmaps are currently in the cache, while the other array contains pointers to the buffer heads that refer to those bitmaps.

The ext2_sb_info structure stores the arrays pertaining to the inode bitmap cache; indexes of block groups are found in the s_inode_bitmap field and pointers to buffer heads are found in the s_inode_bitmap_number field. The corresponding arrays for the block bitmap cache are stored in the s_block_bitmap and s_block_bitmapnumber fields.

The load_inode_bitmap( ) function loads the inode bitmap of a specified block group and returns the cache position in which the bitmap can be found.

If the bitmap is not already in the bitmap cache, load_inode_bitmap( ) invokes read_inode_bitmap( ). The latter function gets the number of the block containing the bitmap from the bg_inode_bitmap field of the group descriptor, and then invokes bread( ) to allocate a new buffer and read the block from disk if it is not already included in the buffer cache.

If the number of block groups in the Ext2 partition is less than or equal to EXT2_MAX_GROUP_LOADED, the index of the cache array position in which the bitmap is inserted always matches the block group index passed as the parameter to the load_inode_bitmap( ) function.

Otherwise, if there are more block groups than cache positions, a bitmap is removed from the cache, if necessary, by using a Least Recently Used (LRU) policy, and the requested bitmap is inserted in the first cache position. Figure 17-3 illustrates the three possible cases in which the bitmap in block group 5 is referenced: where the requested bitmap is already in cache, where the bitmap is not in cache but there is a free position, and where the bitmap is not in cache and there is no free position.

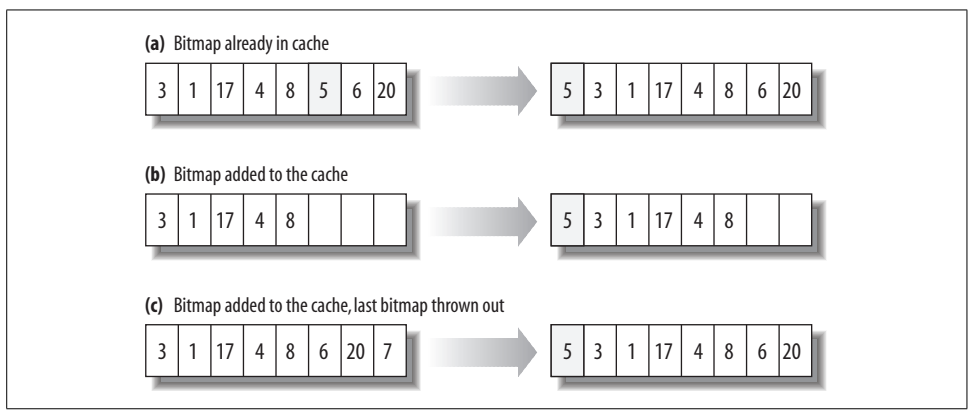


Figure 17-3. Adding a bitmap to the cache

The load_block_bitmap( ) and read_block_bitmap( ) functions are very similar to load_inode_bitmap( ) and read_inode_bitmap( ), but they refer to the block bitmap cache of an Ext2 partition.

Figure 17-4 illustrates the memory data structures of a mounted Ext2 filesystem. In our example, there are three block groups whose descriptors are stored in three blocks on disk; therefore, the s_group_desc field of the ext2_sb_info points to an array of three buffer heads. We have shown just one inode bitmap having index 2 and one block bitmap having index 4, although the kernel may keep 2×EXT2_MAX_GROUP_LOADED bitmaps in the bitmap caches, and even more may be stored in the buffer cache.

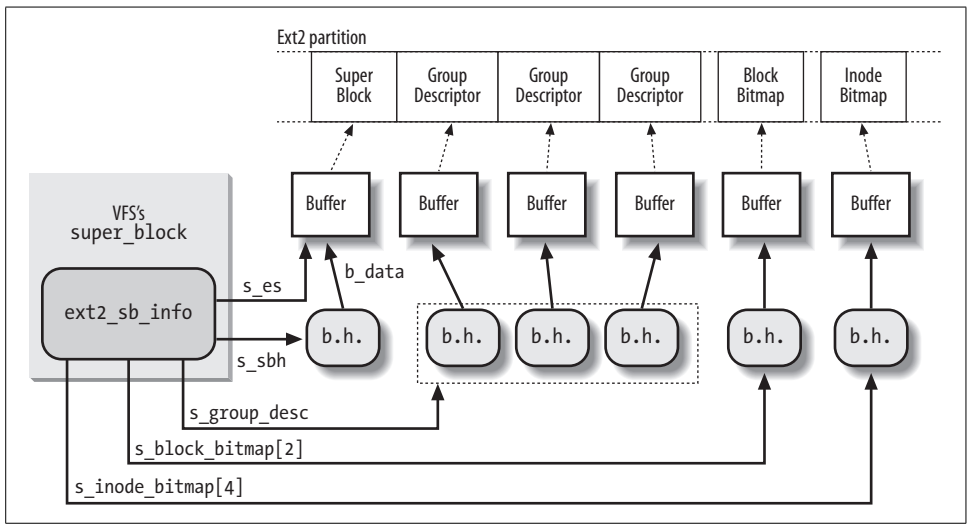


Figure 17-4. Ext2 memory data structures

Creating the Ext2 Filesystem

There are generally two stages to creating a filesystem on a disk. The first step is to format it so that the disk driver can read and write blocks on it. Modern hard disks come preformatted from the factory and need not be reformatted; floppy disks may be formatted on Linux using the *superformat* utility program. The second step involves creating a filesystem, which means setting up the structures described in detail earlier in this chapter.

Ext2 filesystems are created by the *mke2fs* utility program; it assumes the following default options, which may be modified by the user with flags on the command line:

- Block size: 1,024 bytes
- Fragment size: block size (block fragmentation is not implemented)

- Number of allocated inodes: one for each group of 4,096 bytes
- Percentage of reserved blocks: 5 percent

The program performs the following actions:

1. Initializes the superblock and the group descriptors.
2. Optionally, checks whether the partition contains defective blocks; if so, it creates a list of defective blocks.
3. For each block group, reserves all the disk blocks needed to store the superblock, the group descriptors, the inode table, and the two bitmaps.
4. Initializes the inode bitmap and the data map bitmap of each block group to 0.
5. Initializes the inode table of each block group.
6. Creates the */root* directory.
7. Creates the *lost+found* directory, which is used by *e2fsck* to link the lost and found defective blocks.
8. Updates the inode bitmap and the data block bitmap of the block group in which the two previous directories have been created.
9. Groups the defective blocks (if any) in the *lost+found* directory.

Let's consider how an Ext2 1.4 MB floppy disk is initialized by *mke2fs* with the default options.

Once mounted, it appears to the VFS as a volume consisting of 1,390 blocks; each one is 1,024 bytes in length. To examine the disk's contents, we can execute the Unix command:

```
$ dd if=/dev/fd0 bs=1k count=1440 | od -tx1 -Ax > /tmp/dump_hex
```

to get a file containing the hexadecimal dump of the floppy disk contents in the */tmp* directory.*

By looking at that file, we can see that, due to the limited capacity of the disk, a single group descriptor is sufficient. We also notice that the number of reserved blocks is set to 72 (5 percent of 1,440) and, according to the default option, the inode table must include 1 inode for each 4,096 bytes—that is, 360 inodes stored in 45 blocks.

Table 17-7 summarizes how the Ext2 filesystem is created on a floppy disk when the default options are selected.

Table 17-7. Ext2 block allocation for a floppy disk

Block	Content
0	Boot block
1	Superblock

* Some information on an Ext2 filesystem could also be obtained by using the *dumpe2fs* and *debugfs* utility programs.

Table 17-7. Ext2 block allocation for a floppy disk (continued)

Block	Content
2	Block containing a single block group descriptor
3	Data block bitmap
4	Inode bitmap
5–49	Inode table: inodes up to 10: reserved; inode 11: *lost+found*; inodes 12–360: free
50	Root directory (includes `.`, `..`, and *lost+found*)
51	*lost+found* directory (includes `.` and `..`)
52–62	Reserved blocks preallocated for *lost+found* directory
63–1439	Free blocks

Ext2 Methods

Many of the VFS methods described in Chapter 12 have a corresponding Ext2 implementation. Since it would take a whole book to describe all of them, we limit ourselves to briefly reviewing the methods implemented in Ext2. Once the disk and the memory data structures are clearly understood, the reader should be able to follow the code of the Ext2 functions that implement them.

Ext2 Superblock Operations

Many VFS superblock operations have a specific implementation in Ext2, namely `read_inode`, `write_inode`, `put_inode`, `delete_inode`, `put_super`, `write_super`, `statfs`, and `remount_fs`. The addresses of the superblock methods are stored into the `ext2_sops` array of pointers.

Ext2 Inode Operations

Some of the VFS inode operations have a specific implementation in Ext2, which depends on the type of the file to which the inode refers.

If the inode refers to a regular file, all inode operations listed in the `ext2_file_inode_operations` table have a `NULL` pointer, except for the `truncate` operation that is implemented by the `ext2_truncate()` function. Recall that the VFS uses its own generic functions when the corresponding Ext2 method is undefined (a `NULL` pointer).

If the inode refers to a directory, most inode operations listed in the `ext2_dir_inode_operations` table are implemented by specific Ext2 functions (see Table 17-8).

Table 17-8. Ext2 inode operations for directory files

VFS inode operation	Ext2 directory inode method
`create`	`ext2_create()`
`lookup`	`ext2_lookup()`
`link`	`ext2_link()`

Table 17-8. Ext2 inode operations for directory files (continued)

VFS inode operation	Ext2 directory inode method
unlink	ext2_unlink( )
symlink	ext2_symlink( )
mkdir	ext2_mkdir( )
rmdir	ext2_rmdir( )
mknod	ext2_mknod( )
rename	ext2_rename( )

If the inode refers to a symbolic link that can be fully stored inside the inode itself, all inode methods are NULL except for readlink and follow_link, which are implemented by ext2_readlink( ) and ext2_follow_link( ), respectively. The addresses of those methods are stored in the ext2_fast_symlink_inode_operations table. On the other hand, if the inode refers to a long symbolic link that has to be stored inside a data block, the readlink and follow_link methods are implemented by the generic page_readlink( ) and page_follow_link( ) functions, whose addresses are stored in the page_symlink_inode_operations table.

If the inode refers to a character device file, to a block device file, or to a named pipe (see "FIFOs" in Chapter 19), the inode operations do not depend on the filesystem. They are specified in the chrdev_inode_operations, blkdev_inode_operations, and fifo_inode_operations tables, respectively.

Ext2 File Operations

The file operations specific to the Ext2 filesystem are listed in Table 17-9. As you can see, several VFS methods are implemented by generic functions that are common to many filesystems. The addresses of these methods are stored in the ext2_file_operations table.

Table 17-9. Ext2 file operations

VFS file operation	Ext2 method
llseek	generic_file_llseek( )
read	generic_file_read( )
write	generic_file_write( )
ioctl	ext2_ioctl( )
mmap	generic_file_mmap( )
open	generic_file_open( )
release	ext2_release_file( )
fsync	ext2_sync_file( )

Notice that the Ext2's `read` and `write` methods are implemented by the `generic_file_read()` and `generic_file_write()` functions, respectively. These are described in the sections "Reading from a File" and "Writing to a File" in Chapter 15.

Managing Ext2 Disk Space

The storage of a file on disk differs from the view the programmer has of the file in two ways: blocks can be scattered around the disk (although the filesystem tries hard to keep blocks sequential to improve access time), and files may appear to a programmer to be bigger than they really are because a program can introduce holes into them (through the `lseek()` system call).

In this section, we explain how the Ext2 filesystem manages the disk space—how it allocates and deallocates inodes and data blocks. Two main problems must be addressed:

- Space management must make every effort to avoid *file fragmentation*—the physical storage of a file in several, small pieces located in nonadjacent disk blocks. File fragmentation increases the average time of sequential read operations on the files, since the disk heads must be frequently repositioned during the read operation.* This problem is similar to the external fragmentation of RAM discussed in the section "The Buddy System Algorithm" in Chapter 7.
- Space management must be time-efficient; that is, the kernel should be able to quickly derive from a file offset the corresponding logical block number in the Ext2 partition. In doing so, the kernel should limit as much as possible the number of accesses to addressing tables stored on disk, since each such intermediate access considerably increases the average file access time.

Creating Inodes

The `ext2_new_inode()` function creates an Ext2 disk inode, returning the address of the corresponding inode object (or `NULL`, in case of failure). It acts on two parameters: the address `dir` of the inode object that refers to the directory into which the new inode must be inserted and a `mode` that indicates the type of inode being created. The latter argument also includes an `MS_SYNCHRONOUS` flag that requires the current process to be suspended until the inode is allocated. The function performs the following actions:

1. Invokes `new_inode()` to allocate a new inode object and initializes its `i_sb` field to the superblock address stored in `dir->i_sb`.
2. Invokes `down()` on the `s_lock` semaphore included in the parent superblock. As we know, the kernel suspends the current process if the semaphore is already busy.

* Please note that fragmenting a file across block groups (A Bad Thing) is quite different from the not-yet-implemented fragmentation of blocks to store many files in one block (A Good Thing).

3. If the new inode is a directory, tries to place it so that directories are evenly scattered through partially filled block groups. In particular, allocates the new directory in the block group that has the maximum number of free blocks among all block groups that have a greater than average number of free inodes. (The average is the total number of free inodes divided by the number of block groups).
4. If the new inode is not a directory, allocates it in a block group having a free inode. The function selects the group by starting from the one that contains the parent directory and moving farther away from it; to be precise:
   a. Performs a quick logarithmic search starting from the block group that includes the parent directory `dir`. The algorithm searches log(*n*) block groups, where *n* is the total number of block groups. The algorithm jumps further ahead until it finds an available block group—for example, if we call the number of the starting block group *i*, the algorithm considers block groups *i mod* (*n*), *i*+1 *mod* (*n*), *i*+1+2 *mod* (*n*), *i*+1+2+4 *mod* (*n*), etc.
   b. If the logarithmic search failed in finding a block group with a free inode, the function performs an exhaustive linear search starting from the block group that includes the parent directory `dir`.
5. Invokes `load_inode_bitmap()` to get the inode bitmap of the selected block group and searches for the first null bit into it, thus obtaining the number of the first free disk inode.
6. Allocates the disk inode: sets the corresponding bit in the inode bitmap and marks the buffer containing the bitmap as dirty. Moreover, if the filesystem has been mounted specifying the `MS_SYNCHRONOUS` flag, invokes `ll_rw_block()` and waits until the write operation terminates (see the section "Mounting a Generic Filesystem" in Chapter 12).
7. Decrements the `bg_free_inodes_count` field of the group descriptor. If the new inode is a directory, increments the `bg_used_dirs_count` field. Marks the buffer containing the group descriptor as dirty.
8. Decrements the `s_free_inodes_count` field of the disk superblock and marks the buffer containing it as dirty. Sets the `s_dirt` field of the VFS's superblock object to 1.
9. Initializes the fields of the inode object. In particular, sets the inode number `i_no` and copies the value of `xtime.tv_sec` into `i_atime`, `i_mtime`, and `i_ctime`. Also loads the `i_block_group` field in the `ext2_inode_info` structure with the block group index. Refer to Table 17-3 for the meaning of these fields.
10. Inserts the new inode object into the hash table `inode_hashtable` and invokes `mark_inode_dirty()` to move the inode object into the superblock's dirty inode list (see the section "Inode Objects" in Chapter 12).
11. Invokes `up()` on the `s_lock` semaphore included in the parent superblock.
12. Returns the address of the new inode object.

Deleting Inodes

The ext2_free_inode( ) function deletes a disk inode, which is identified by an inode object whose address is passed as the parameter. The kernel should invoke the function after a series of cleanup operations involving internal data structures and the data in the file itself. It should come after the inode object has been removed from the inode hash table, after the last hard link referring to that inode has been deleted from the proper directory and after the file is truncated to 0 length to reclaim all its data blocks (see the section "Releasing a Data Block" later in this chapter). It performs the following actions:

1. Invokes down( ) on the s_lock semaphore included in the parent superblock to get exclusive access to the superblock object.
2. Invokes clear_inode( ) to perform the following operations:
   a. Invokes invalidate_inode_buffers( ) to remove the dirty buffers that belong to the inode from its i_dirty_buffers and i_dirty_data_buffers lists (see the section "Buffer Head Data Structures" in Chapter 14).
   b. If the I_LOCK flag of the inode is set, some of the inode's buffers are involved in I/O data transfers; the function suspends the current process until these I/O data transfers terminate.
   c. Invokes the clear_inode method of the superblock object, if defined; the Ext2 filesystem does not define it.
   d. Sets the state of the inode to I_CLEAR (the inode object contents are no longer meaningful).
3. Computes the index of the block group containing the disk inode from the inode number and the number of inodes in each block group.
4. Invokes load_inode_bitmap( ) to get the inode bitmap.
5. Increments the bg_free_inodes_count field of the group descriptor. If the deleted inode is a directory, decrements the bg_used_dirs_count field. Marks the buffer that contains the group descriptor as dirty.
6. Increments the s_free_inodes_count field of the disk superblock and marks the buffer that contains it as dirty. Also sets the s_dirt field of the superblock object to 1.
7. Clears the bit corresponding to the disk inode in the inode bitmap and marks the buffer that contains the bitmap as dirty. Moreover, if the filesystem has been mounted with the MS_SYNCHRONIZE flag, invokes ll_rw_block( ) and waits until the write operation on the bitmap's buffer terminates.
8. Invokes up( ) on the s_lock semaphore included in the parent superblock object.

Data Blocks Addressing

Each nonempty regular file consists of a group of data blocks. Such blocks may be referred to either by their relative position inside the file (their *file block number*) or by their position inside the disk partition (their logical block number, explained in the section "Buffer Heads" in Chapter 13).

Deriving the logical block number of the corresponding data block from an offset *f* inside a file is a two-step process:

1. Derive from the offset *f* the file block number—the index of the block that contains the character at offset *f*.
2. Translate the file block number to the corresponding logical block number.

Since Unix files do not include any control characters, it is quite easy to derive the file block number containing the f^{th} character of a file: simply take the quotient of *f* and the filesystem's block size and round down to the nearest integer.

For instance, let's assume a block size of 4 KB. If *f* is smaller than 4,096, the character is contained in the first data block of the file, which has file block number 0. If *f* is equal to or greater than 4,096 and less than 8,192, the character is contained in the data block that has file block number 1, and so on.

This is fine as far as file block numbers are concerned. However, translating a file block number into the corresponding logical block number is not nearly as straightforward, since the data blocks of an Ext2 file are not necessarily adjacent on disk.

The Ext2 filesystem must therefore provide a method to store the connection between each file block number and the corresponding logical block number on disk. This mapping, which goes back to early versions of Unix from AT&T, is implemented partly inside the inode. It also involves some specialized blocks that contain extra pointers, which are an inode extension used to handle large files.

The `i_block` field in the disk inode is an array of `EXT2_N_BLOCKS` components that contain logical block numbers. In the following discussion, we assume that `EXT2_N_BLOCKS` has the default value, namely 15. The array represents the initial part of a larger data structure, which is illustrated in Figure 17-5. As can be seen in the figure, the 15 components of the array are of 4 different types:

- The first 12 components yield the logical block numbers corresponding to the first 12 blocks of the file—to the blocks that have file block numbers from 0 to 11.
- The component at index 12 contains the logical block number of a block that represents a second-order array of logical block numbers. They correspond to the file block numbers ranging from 12 to *b*/4+11, where *b* is the filesystem's block size (each logical block number is stored in 4 bytes, so we divide by 4 in the formula). Therefore, the kernel must look in this component for a pointer to a block, and then look in that block for another pointer to the ultimate block that contains the file contents.

- The component at index 13 contains the logical block number of a block containing a second-order array of logical block numbers; in turn, the entries of this second-order array point to third-order arrays, which store the logical block numbers that correspond to the file block numbers ranging from $b/4+12$ to $(b/4)^2+(b/4)+11$.
- Finally, the component at index 14 uses triple indirection: the fourth-order arrays store the logical block numbers corresponding to the file block numbers ranging from $(b/4)^2+(b/4)+12$ to $(b/4)^3+(b/4)^2+(b/4)+11$ upward.

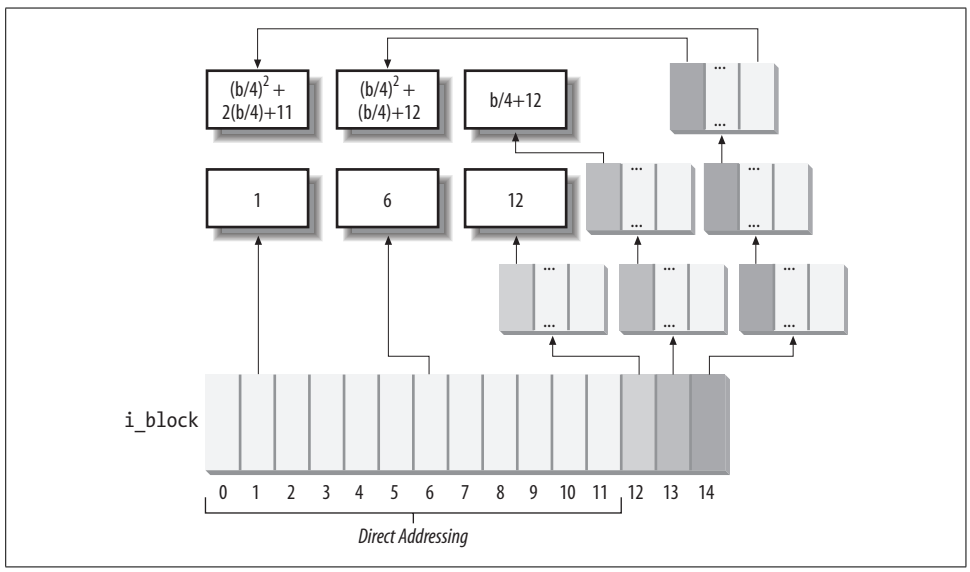


Figure 17-5. Data structures used to address the file's data blocks

In Figure 17-5, the number inside a block represents the corresponding file block number. The arrows, which represent logical block numbers stored in array components, show how the kernel finds its way to reach the block that contains the actual contents of the file.

Notice how this mechanism favors small files. If the file does not require more than 12 data blocks, any data can be retrieved in two disk accesses: one to read a component in the `i_block` array of the disk inode and the other to read the requested data block. For larger files, however, three or even four consecutive disk accesses may be needed to access the required block. In practice, this is a worst-case estimate, since dentry, buffer, and page caches contribute significantly to reduce the number of real disk accesses.

Notice also how the block size of the filesystem affects the addressing mechanism, since a larger block size allows the Ext2 to store more logical block numbers inside a single block. Table 17-10 shows the upper limit placed on a file's size for each block size and each addressing mode. For instance, if the block size is 1,024 bytes and the

file contains up to 268 kilobytes of data, the first 12 KB of a file can be accessed through direct mapping and the remaining 13–268 KB can be addressed through simple indirection. Files larger than 2 GB must be opened on 32-bit architectures by specifying the `O_LARGEFILE` opening flag. In any case, the Ext2 filesystem puts an upper limit on the file size equal to 2 TB minus 4,096 bytes.

Table 17-10. File size upper limits for data block addressing

Block Size	Direct	1-Indirect	2-Indirect	3-Indirect
1,024	12 KB	268 KB	64.26 MB	16.06 GB
2,048	24 KB	1.02 MB	513.02 MB	256.5 GB
4,096	48 KB	4.04 MB	4 GB	~ 2 TB

File Holes

A *file hole* is a portion of a regular file that contains null characters and is not stored in any data block on disk. Holes are a long-standing feature of Unix files. For instance, the following Unix command creates a file in which the first bytes are a hole:

```
$ echo -n "X" | dd of=/tmp/hole bs=1024 seek=6
```

Now */tmp/hole* has 6,145 characters (6,144 null characters plus an X character), yet the file occupies just one data block on disk.

File holes were introduced to avoid wasting disk space. They are used extensively by database applications and, more generally, by all applications that perform hashing on files.

The Ext2 implementation of file holes is based on dynamic data block allocation: a block is actually assigned to a file only when the process needs to write data into it. The `i_size` field of each inode defines the size of the file as seen by the program, including the hole, while the `i_blocks` field stores the number of data blocks effectively assigned to the file (in units of 512 bytes).

In our earlier example of the `dd` command, suppose the */tmp/hole* file was created on an Ext2 partition that has blocks of size 4,096. The `i_size` field of the corresponding disk inode stores the number 6,145, while the `i_blocks` field stores the number 8 (because each 4,096-byte block includes eight 512-byte blocks). The second element of the `i_block` array (corresponding to the block having file block number 1) stores the logical block number of the allocated block, while all other elements in the array are null (see Figure 17-6).

Allocating a Data Block

When the kernel has to locate a block holding data for an Ext2 regular file, it invokes the `ext2_get_block()` function. If the block does not exist, the function automatically allocates the block to the file. Remember that this function is invoked every

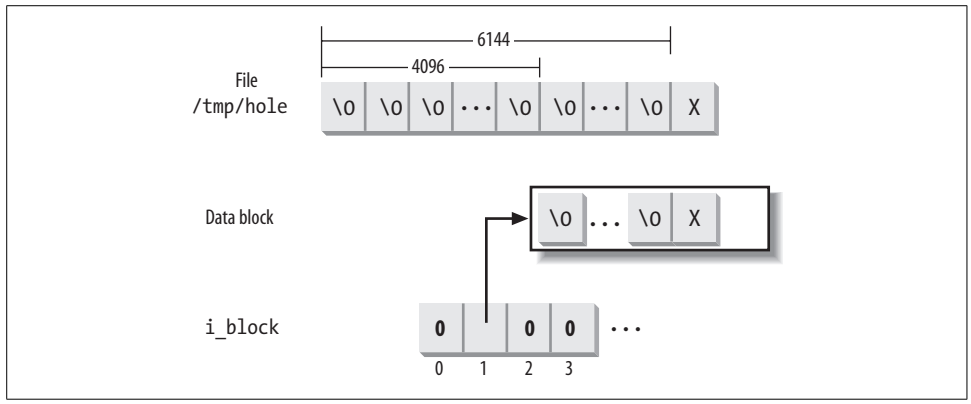


Figure 17-6. A file with an initial hole

time the kernel issues a read or write operation on a Ext2 regular file (see the sections "Reading from a File" and "Writing to a File" in Chapter 15).

The `ext2_get_block()` function handles the data structures already described in the section "Data Blocks Addressing," and when necessary, invokes the `ext2_alloc_block()` function to actually search for a free block in the Ext2 partition.

To reduce file fragmentation, the Ext2 filesystem tries to get a new block for a file near the last block already allocated for the file. Failing that, the filesystem searches for a new block in the block group that includes the file's inode. As a last resort, the free block is taken from one of the other block groups.

The Ext2 filesystem uses preallocation of data blocks. The file does not get just the requested block, but rather a group of up to eight adjacent blocks. The `i_prealloc_count` field in the `ext2_inode_info` structure stores the number of data blocks preallocated to a file that are still unused, and the `i_prealloc_block` field stores the logical block number of the next preallocated block to be used. Any preallocated blocks that remain unused are freed when the file is closed, when it is truncated, or when a write operation is not sequential with respect to the write operation that triggered the block preallocation.

The `ext2_alloc_block()` function receives as parameters a pointer to an inode object and a *goal*. The goal is a logical block number that represents the preferred position of the new block. The `ext2_getblk()` function sets the goal parameter according to the following heuristic:

1. If the block that is being allocated and the previously allocated block have consecutive file block numbers, the goal is the logical block number of the previous block plus 1; it makes sense that consecutive blocks as seen by a program should be adjacent on disk.
2. If the first rule does not apply and at least one block has been previously allocated to the file, the goal is one of these blocks' logical block numbers. More precisely, it is the logical block number of the already allocated block that precedes the block to be allocated in the file.

3. If the preceding rules do not apply, the goal is the logical block number of the first block (not necessarily free) in the block group that contains the file's inode.

The `ext2_alloc_block()` function checks whether the goal refers to one of the preallocated blocks of the file. If so, it allocates the corresponding block and returns its logical block number; otherwise, the function discards all remaining preallocated blocks and invokes `ext2_new_block()`.

This latter function searches for a free block inside the Ext2 partition with the following strategy:

1. If the preferred block passed to `ext2_alloc_block()`, the goal, is free, and the function allocates the block.
2. If the goal is busy, the function checks whether one of the next 64 blocks after the preferred block is free.
3. If no free block is found in the near vicinity of the preferred block, the function considers all block groups, starting from the one including the goal. For each block group, the function does the following:
   a. Looks for a group of at least eight adjacent free blocks.
   b. If no such group is found, looks for a single free block.

The search ends as soon as a free block is found. Before terminating, the `ext2_new_block()` function also tries to preallocate up to eight free blocks adjacent to the free block found and sets the `i_prealloc_block` and `i_prealloc_count` fields of the disk inode to the proper block location and number of blocks.

Releasing a Data Block

When a process deletes a file or truncates it to 0 length, all its data blocks must be reclaimed. This is done by `ext2_truncate()`, which receives the address of the file's inode object as its parameter. The function essentially scans the disk inode's `i_block` array to locate all data blocks and all blocks used for the indirect addressing. These blocks are then released by repeatedly invoking `ext2_free_blocks()`.

The `ext2_free_blocks()` function releases a group of one or more adjacent data blocks. Besides its use by `ext2_truncate()`, the function is invoked mainly when discarding the preallocated blocks of a file (see the earlier section "Allocating a Data Block"). Its parameters are:

`inode`
: The address of the inode object that describes the file

`block`
: The logical block number of the first block to be released

`count`
: The number of adjacent blocks to be released

The function invokes down( ) on the s_lock superblock's semaphore to get exclusive access to the filesystem's superblock, and then performs the following actions for each block to be released:

1. Gets the block bitmap of the block group, including the block to be released
2. Clears the bit in the block bitmap that corresponds to the block to be released and marks the buffer that contains the bitmap as dirty
3. Increments the bg_free_blocks_count field in the block group descriptor and marks the corresponding buffer as dirty
4. Increments the s_free_blocks_count field of the disk superblock, marks the corresponding buffer as dirty, and sets the s_dirt flag of the superblock object
5. If the filesystem has been mounted with the MS_SYNCHRONOUS flag set, invokes ll_rw_block( ) and waits until the write operation on the bitmap's buffer terminates

Finally, the function invokes up( ) to release the superblock's s_lock semaphore.

The Ext3 Filesystem

In this section we'll briefly describe the enhanced filesystem that has evolved from Ext2, named *Ext3*. The new filesystem has been designed with two simple concepts in mind:

- To be a journaling filesystem (see the next section)
- To be, as much as possible, compatible with the old Ext2 filesystem

Ext3 achieves both the goals very well. In particular, it is largely based on Ext2, so its data structures on disk are essentially identical to those of an Ext2 filesystem. As a matter of fact, if an Ext3 filesystem has been cleanly unmounted, it can be remounted as an Ext2 filesystem; conversely, creating a journal of an Ext2 filesystem and remounting it as an Ext3 filesystem is a simple, fast operation.

Thanks to the compatibility between Ext3 and Ext2, most descriptions in the previous sections of this chapter apply to Ext3 as well. Therefore, in this section, we focus on the new feature offered by Ext3—"the journal."

Journaling Filesystems

As disks became larger, one design choice of traditional Unix filesystems (like Ext2) turns out to be inappropriate. As we know from Chapter 14, updates to filesystem blocks might be kept in dynamic memory for long period of time before being flushed to disk. A dramatic event like a power-down failure or a system crash might thus leave the filesystem in an inconsistent state. To overcome this problem, each traditional Unix filesystem is checked before being mounted; if it has not been properly unmounted, then a specific program executes an exhaustive, time-consuming check and fixes all filesystem's data structures on disk.

For instance, the Ext2 filesystem status is stored in the `s_mount_state` field of the superblock on disk. The *e2fsck* utility program is invoked by the boot script to check the value stored in this field; if it is not equal to `EXT2_VALID_FS`, the filesystem was not properly unmounted, and therefore *e2fsck* starts checking all disk data structures of the filesystem.

Clearly, the time spent checking the consistency of a filesystem depends mainly on the number of files and directories to be examined; therefore, it also depends on the disk size. Nowadays, with filesystems reaching hundreds of gigabytes, a single consistency check may take hours. The involved downtime is unacceptable for any production environment or high-availability server.

The goal of a *journaling filesystem* is to avoid running time-consuming consistency checks on the whole filesystem by looking instead in a special disk area that contains the most recent disk write operations named *journal*. Remounting a journaling filesystem after a system failure is a matter of few seconds.

The Ext3 Journaling Filesystem

The idea behind Ext3 journaling is to perform any high-level change to the filesystem in two steps. First, a copy of the blocks to be written is stored in the journal; then, when the I/O data transfer to the journal is completed (in short, data is *committed to the journal*), the blocks are written in the filesystem. When the I/O data transfer to the filesystem terminates (data is *committed to the filesystem*), the copies of the blocks in the journal are discarded.

While recovering after a system failure, the *e2fsck* program distinguishes the following two cases:

The system failure occurred before a commit to the journal. Either the copies of the blocks relative to the high-level change are missing from the journal or they are incomplete; in both cases, *e2fsck* ignores them.

The system failure occurred after a commit to the journal. The copies of the blocks are valid and *e2fsck* writes them into the filesystem.

In the first case, the high-level change to the filesystem is lost, but the filesystem state is still consistent. In the second case, *e2fsck* applies the whole high-level change, thus fixing any inconsistency due to unfinished I/O data transfers into the filesystem.

Don't expect too much from a journaling filesystem; it ensures consistency only at the system call level. For instance, a system failure that occurs while you are copying a large file by issuing several `write()` system calls will interrupt the copy operation, thus the duplicated file will be shorter than the original one.

Furthermore, journaling filesystems do not usually copy all blocks into the journal. In fact, each filesystem consists of two kinds of blocks: those containing the so-called *metadata* and those containing regular data. In the case of Ext2 and Ext3, there are

six kinds of metadata: superblocks, group block descriptors, inodes, blocks used for indirect addressing (indirection blocks), data bitmap blocks, and inode bitmap blocks. Other filesystems may use different metadata.

Most journaling filesystems, like ReiserFS, SGI's XFS, and IBM's JFS, limit themselves to log the operations affecting metadata. In fact, metadata's log records are sufficient to restore the consistency of the on-disk filesystem data structures. However, since operations on blocks of file data are not logged, nothing prevents a system failure from corrupting the contents of the files.

The Ext3 filesystem, however, can be configured to log the operations affecting both the filesystem metadata and the data blocks of the files. Since logging every kind of write operation leads to a significant performance penalty, Ext3 lets the system administrator decide what has to be logged; in particular, it offers three different journaling modes:

Journal
: All filesystem data and metadata changes are logged into the journal. This mode minimizes the chance of losing the updates made to each file, but it requires many additional disk accesses. For example, when a new file is created, all its data blocks must be duplicated as log records. This is the safest and slowest Ext3 journaling mode.

Ordered
: Only changes to filesystem metadata are logged into the journal. However, the Ext3 filesystem groups metadata and relative data blocks so that data blocks are written to disk *before* the metadata. This way, the chance to have data corruption inside the files is reduced; for instance, any write access that enlarges a file is guaranteed to be fully protected by the journal. This is the default Ext3 journaling mode.

Writeback
: Only changes to filesystem metadata are logged; this is the method found on the other journaling filesystems and is the fastest mode.

The journaling mode of the Ext3 filesystem is specified by an option of the *mount* system command. For instance, to mount an Ext3 filesystem stored in the */dev/sda2* partition on the */jdisk* mount point with the "writeback" mode, the system administrator can type the command:

```
# mount -t ext3 -o data=writeback /dev/sda2 /jdisk
```

The Journaling Block Device Layer

The Ext3 journal is usually stored in a hidden file named *.journal* located in the root directory of the filesystem.

The Ext3 filesystem does not handle the journal on its own; rather, it uses a general kernel layer named *Journaling Block Device*, or *JBD*. Right now, only Ext3 uses the JBD layer, but other filesystems might use it in the future.

The JBD layer is a rather complex piece of software. The Ext3 filesystem invokes the JBD routines to ensure that its subsequent operations don't corrupt the disk data structures in case of system failure. However, JBD typically uses the same disk to log the changes performed by the Ext3 filesystem, and it is therefore vulnerable to system failures as much as Ext3. In other words, JBD must also protect itself from any system failure that could corrupt the journal.

Therefore, the interaction between Ext3 and JBD is essentially based on three fundamental units:

Log record
: Describes a single update of a disk block of the journaling filesystem.

Atomic operation handle
: Includes log records relative to a single high-level change of the filesystem; typically, each system call modifying the filesystem gives rise to a single atomic operation handle.

Transaction
: Includes several atomic operation handles whose log records are marked valid for *e2fsck* at the same time.

Log records

A *log record* is essentially the description of a low-level operation that is going to be issued by the filesystem. In some journaling filesystems, the log record consists of exactly the span of bytes modified by the operation, together with the starting position of the bytes inside the filesystem. The JBD layer, however, uses log records consisting of the whole buffer modified by the low-level operation. This approach may waste a lot of journal space (for instance, when the low-level operation just changes the value of a bit in a bitmap), but it is also much faster because the JBD layer can work directly with buffers and their buffer heads.

Log records are thus represented inside the journal as normal blocks of data (or metadata). Each such block, however, is associated with a small tag of type `journal_block_tag_t`, which stores the logical block number of the block inside the filesystem and a few status flags.

Later, whenever a buffer is being considered by the JBD, either because it belongs to a log record or because it is a data block that should be flushed to disk before the corresponding metadata block (in the "ordered" journaling mode), the kernel attaches a `journal_head` data structure to the buffer head. In this case, the `b_private` field of the buffer head stores the address of the `journal_head` data structure and the `BH_JBD` flag is set (see the section "Buffer Heads" in Chapter 13).

Atomic operation handles

Any system call modifying the filesystem is usually split into a series of low-level operations that manipulate disk data structures.

For instance, suppose that Ext3 must satisfy a user request to append a block of data to a regular file. The filesystem layer must determine the last block of the file, locate a free block in the filesystem, update the data block bitmap inside the proper block group, store the logical number of the new block either in the file's inode or in an indirect addressing block, write the contents of the new block, and finally, update several fields of the inode. As you see, the append operation translates into many lower-level operations on the data and metadata blocks of the filesystem.

Now, just imagine what could happen if a system failure occurred in the middle of an append operation, when some of the lower-level manipulations have already been executed while others have not. Of course, the scenario could be even worse, with high-level operations affecting two or more files (for example, moving a file from one directory to another).

To prevent data corruption, the Ext3 filesystem must ensure that each system call is handled in an atomic way. An *atomic operation handle* is a set of low-level operations on the disk data structures that correspond to a single high-level operation. When recovering from a system failure, the filesystem ensures that either the whole high-level operation is applied or none of its low-level operations is.

Any atomic operation handle is represented by a descriptor of type `handle_t`. To start an atomic operation, the Ext3 filesystem invokes the `journal_start()` JBD function, which allocates, if necessary, a new atomic operation handle and inserts it into the current transactions (see the next section). Since any low-level operation on the disk might suspend the process, the address of the active handle is stored in the `journal_info` field of the process descriptor. To notify that an atomic operation is completed, the Ext3 filesystem invokes the `journal_stop()` function.

Transactions

For reasons of efficiency, the JBD layer manages the journal by grouping the log records that belong to several atomic operation handles into a single *transaction*. Furthermore, all log records relative to a handle must be included in the same transaction.

All log records of a transaction are stored in consecutive blocks of the journal. The JBD layer handles each transaction as a whole. For instance, it reclaims the blocks used by a transaction only after all data included in its log records is committed to the filesystem.

As soon as it is created, a transaction may accept log records of new handles. The transaction stops accepting new handles when either of the following occurs:

- A fixed amount of time has elapsed, typically 5 seconds.
- There are no free blocks in the journal left for a new handle

A transaction is represented by a descriptor of type `transaction_t`. The most important field is `t_state`, which describes the current status of the transaction.

Essentially, a transaction can be:

Complete
: All log records included in the transaction have been physically written onto the journal. When recovering from a system failure, *e2fsck* considers every complete transaction of the journal and writes the corresponding blocks into the filesystem. In this case, the `i_state` field stores the value `T_FINISHED`.

Incomplete
: At least one log record included in the transaction has not yet been physically written to the journal, or new log records are still being added to the transaction. In case of system failure, the image of the transaction stored in the journal is likely not up to date. Therefore, when recovering from a system failure, *e2fsck* does not trust the incomplete transactions in the journal and skips them. In this case, the `i_state` field stores one of the following values:

  `T_RUNNING`
  : Still accepting new atomic operation handles.

  `T_LOCKED`
  : Not accepting new atomic operation handles, but some of them are still unfinished.

  `T_FLUSH`
  : All atomic operation handles have finished, but some log records are still being written to the journal.

  `T_COMMIT`
  : All log records of the atomic operation handles have been written to disk, and the transaction is marked as completed on the journal.

At any given instance, the journal may include several transactions. Just one of them is in the `T_RUNNING` state—it is the *active transaction* that is accepting the new atomic operation handle requests issued by the Ext3 filesystem.

Several transactions in the journal might be incomplete because the buffers containing the relative log records have not yet been written to the journal.

A complete transaction is deleted from the journal only when the JBD layer verifies that all buffers described by the log records have been successfully written onto the Ext3 filesystem. Therefore, the journal can include at most one incomplete transaction and several complete transactions. The log records of a complete transaction have been written to the journal but some of the corresponding buffers have yet to be written onto the filesystem.

How Journaling Works

Let's try to explain how journaling works with an example: the Ext3 filesystem layer receives a request to write some data blocks of a regular file.

As you might easily guess, we are not going to describe in detail every single operation of the Ext3 filesystem layer and of the JBD layer. There would be far too many issues to be covered! However, we describe the essential actions:

1. The service routine of the `write()` system call triggers the `write` method of the file object associated with the Ext3 regular file. For Ext3, this method is implemented by the `generic_file_write()` function, already described in the section "Writing to a File" in Chapter 15.
2. The `generic_file_write()` function invokes the `prepare_write` method of the `address_space` object several times, once for every page of data involved by the write operation. For Ext3, this method is implemented by the `ext3_prepare_write()` function.
3. The `ext3_prepare_write()` function starts a new atomic operation by invoking the `journal_start()` JBD function. The handle is added to the active transaction. Actually, the atomic operation handle is created only when executing the first invocation of the `journal_start()` function. Following invocations verify that the `journal_info` field of the process descriptor is already set and use the referenced handle.
4. The `ext3_prepare_write()` function invokes the `block_prepare_write()` function already described in Chapter 15, passing to it the address of the `ext3_get_block()` function. Remember that `block_prepare_write()` takes care of preparing the buffers and the buffer heads of the file's page.
5. When the kernel must determine the logical number of a block of the Ext3 filesystem, it executes the `ext3_get_block()` function. This function is actually similar to `ext2_get_block()`, which is described in the earlier section "Allocating a Data Block." A crucial difference, however, is that the Ext3 filesystem invokes functions of the JBD layer to ensure that the low-level operations are logged:
   - *Before* issuing a low-level write operation on a metadata block of the filesystem, the function invokes `journal_get_write_access()`. Basically, this latter function adds the metadata buffer to a list of the active transaction. However, it must also check whether the metadata is included in an older incomplete transaction of the journal; in this case, it duplicates the buffer to make sure that the older transactions are committed with the old content.
   - *After* updating the buffer containing the metadata block, the Ext3 filesystem invokes `journal_dirty_metadata()` to move the metadata buffer to the proper dirty list of the active transaction and to log the operation in the journal.

   Notice that metadata buffers handled by the JBD layer are not usually included in the dirty lists of buffers of the inode, so they are not written to disk by the normal disk cache flushing mechanisms described in Chapter 14.
6. If the Ext3 filesystem has been mounted in "journal" mode, the `ext3_prepare_write()` function also invokes `journal_get_write_access()` on every buffer touched by the write operation.

7. Control returns to the generic_file_write() function, which updates the page with the data stored in the User Mode address space and then invokes the commit_write method of the address_space object. For Ext3, this method is implemented by the ext3_commit_write() function.
8. If the Ext3 filesystem has been mounted in "journal" mode, the ext3_commit_write() function invokes journal_dirty_metadata() on every buffer of data (not metadata) in the page. This way, the buffer is included in the proper dirty list of the active transaction and not in the dirty list of the owner inode; moreover, the corresponding log records are written to the journal.
9. If the Ext3 filesystem has been mounted in "ordered" mode, the ext3_commit_write() function invokes the journal_dirty_data() function on every buffer of data in the page to insert the buffer in a proper list of the active transactions. The JBD layer ensures that all buffers in this list are written to disk before the metadata buffers of the transaction. No log record is written onto the journal.
10. If the Ext3 filesystem has been mounted in "ordered" or "writeback" mode, the ext3_commit_write() function executes the normal generic_commit_write() function described in Chapter 15, which inserts the data buffers in the list of the dirty buffers of the owner inode.
11. Finally, ext3_commit_write() invokes journal_stop() to notify the JBD layer that the atomic operation handle is closed.
12. The service routine of the write() system call terminates here. However, the JBD layer has not finished its work. Eventually, our transaction becomes complete when all its log records have been physically written to the journal. Then journal_commit_transaction() is executed.
13. If the Ext3 filesystem has been mounted in "ordered" mode, the journal_commit_transaction() function activates the I/O data transfers for all data buffers included in the list of the transaction and waits until all data transfers terminate.
14. The journal_commit_transaction() function activates the I/O data transfers for all metadata buffers included in the transaction (and also for all data buffers, if Ext3 was mounted in "journal" mode).
15. Periodically, the kernel activates a checkpoint activity for every complete transaction in the journal. The checkpoint basically involves verifying whether the I/O data transfers triggered by journal_commit_transaction() have successfully terminated. If so, the transaction can be deleted from the journal.

Of course, the log records in the journal never play an active role until a system failure occurs. Only in this case, in fact, does the *e2fsck* utility program scan the journal stored in the filesystem and reschedule all write operations described by the log records of the complete transactions.